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Title: MiniBooNE Cross Section Measurement

Author(s): Pavlovic, Zarko

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# MiniBooNE Cross Section Measurement

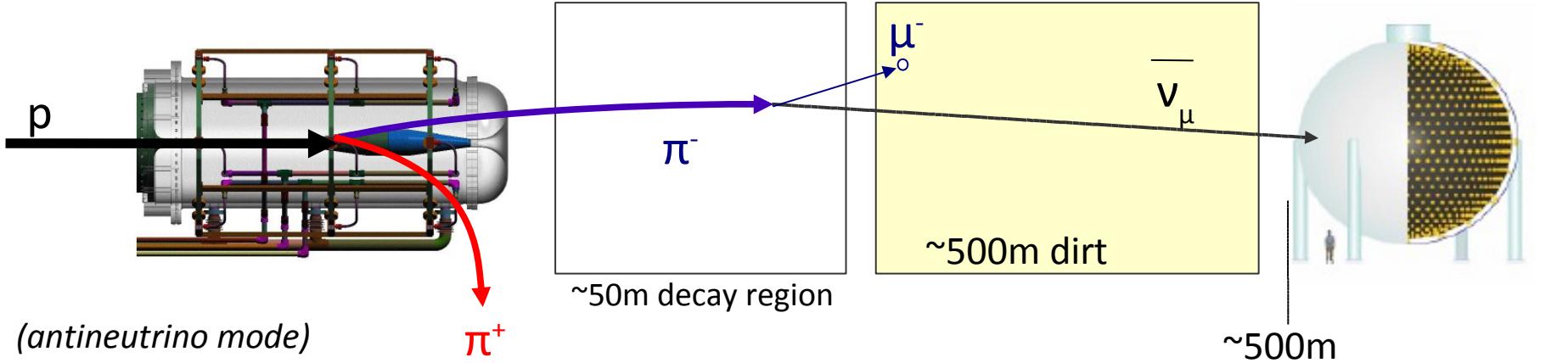
Žarko Pavlović

Los Alamos National Laboratory

# Outline

- Booster Neutrino Beamline & MiniBooNE detector
- Cross section measurements with MiniBooNE
- New results
  - Anti neutrino CCQE (J. Grange)
- Forthcoming results
  - NC Elastic (R. Dharmapalan)
  - CC inclusive (M. Tzanov)
- Conclusion

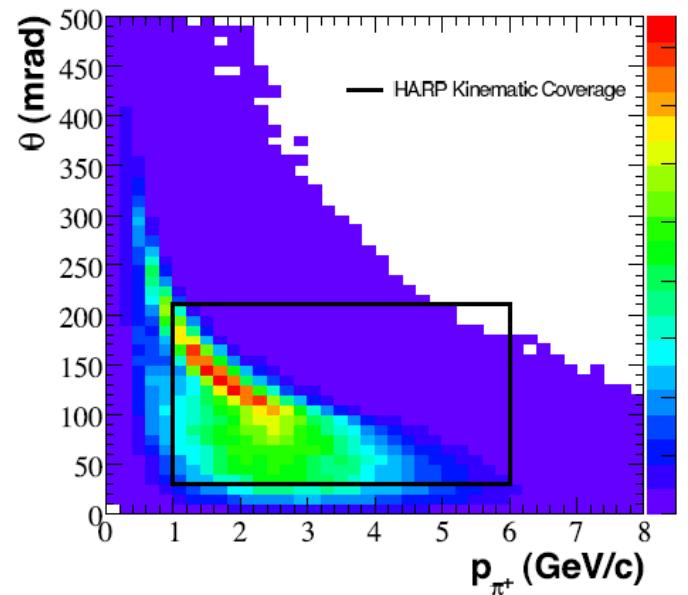
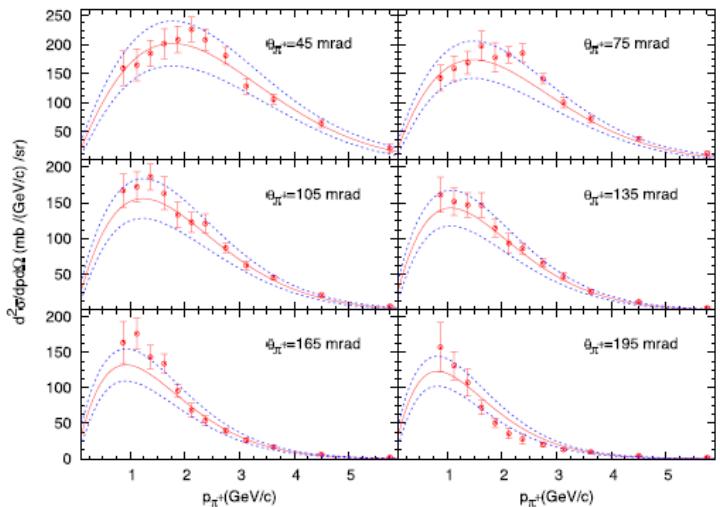
# Booster Neutrino Beam



- Designed to study LSND anomaly - similar L/E as LSND
  - MiniBooNE  $\sim 500\text{m}/\sim 500\text{MeV}$
  - LSND  $\sim 30\text{m}/\sim 30\text{MeV}$
- Horn focused neutrino beam ( $p+\text{Be}$ )
  - Horn polarity  $\rightarrow$  neutrino or anti-neutrino mode
- Mineral oil Cherenkov detector

# Hadron production in BNB target

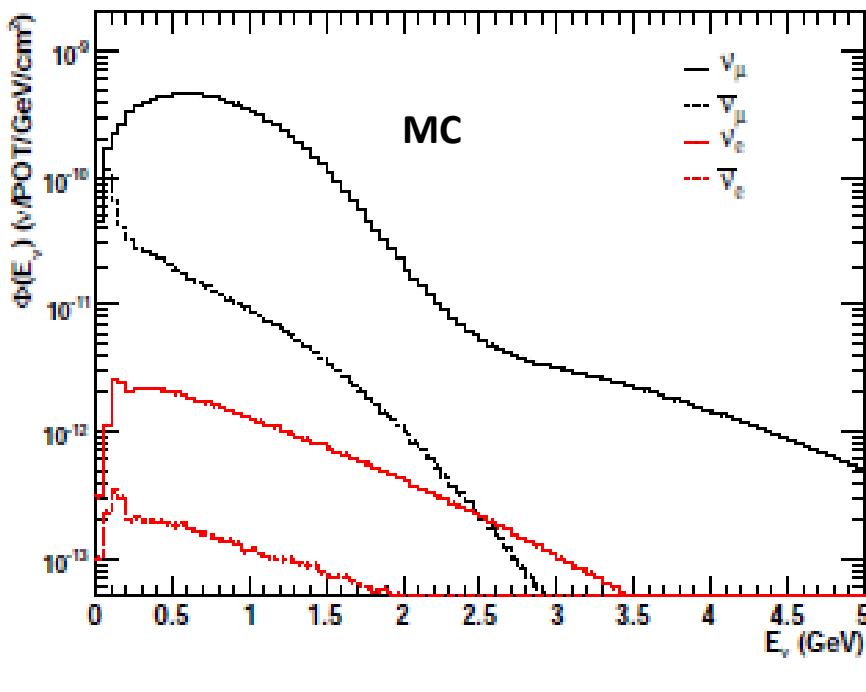
- Major uncertainty in the neutrino flux prediction due to pion production in p+Be interactions
- Need to know neutrino flux for precise cross section measurements
- Used external pi+ & pi- production data (HARP, BNL E910)
- HARP measured production on Be target using 8.9GeV protons
- Covers phase space contributing to 78% of neutrino flux from pi+ (76% from pi- in antineutrino mode)
- Overall 9% flux uncertainty – dominant error in cross section measurement



# Predicted flux

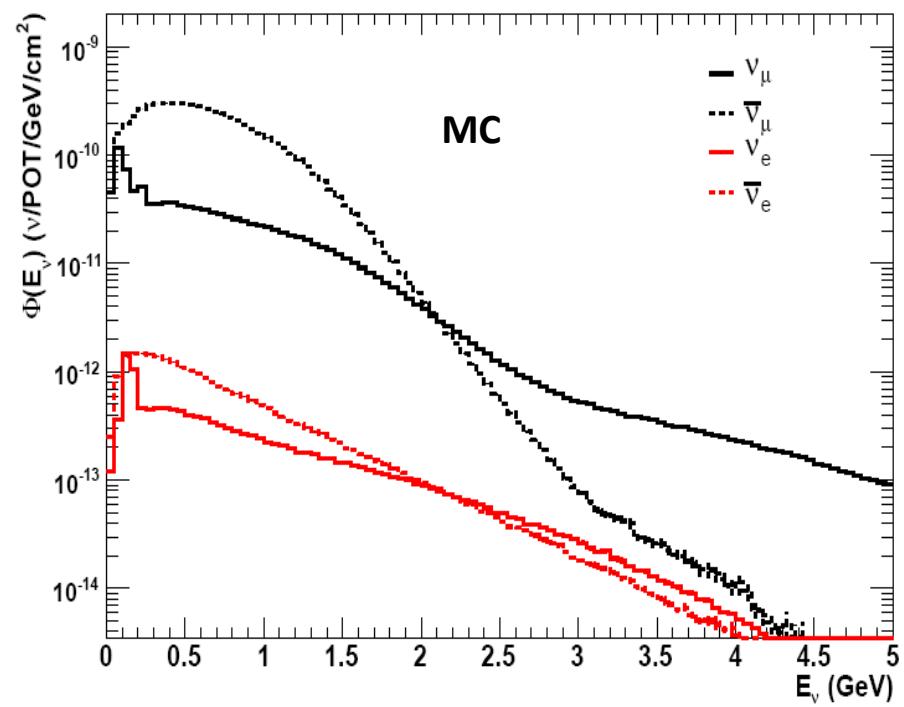
Neutrino mode

$\nu_\mu$	93.6%
$\bar{\nu}_\mu$	5.8%
$\nu_e + \bar{\nu}_e$	0.6%



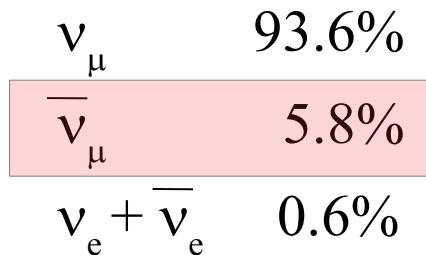
Anti-neutrino mode

$\nu_\mu$	15.7%
$\bar{\nu}_\mu$	83.7%
$\nu_e + \bar{\nu}_e$	0.6%



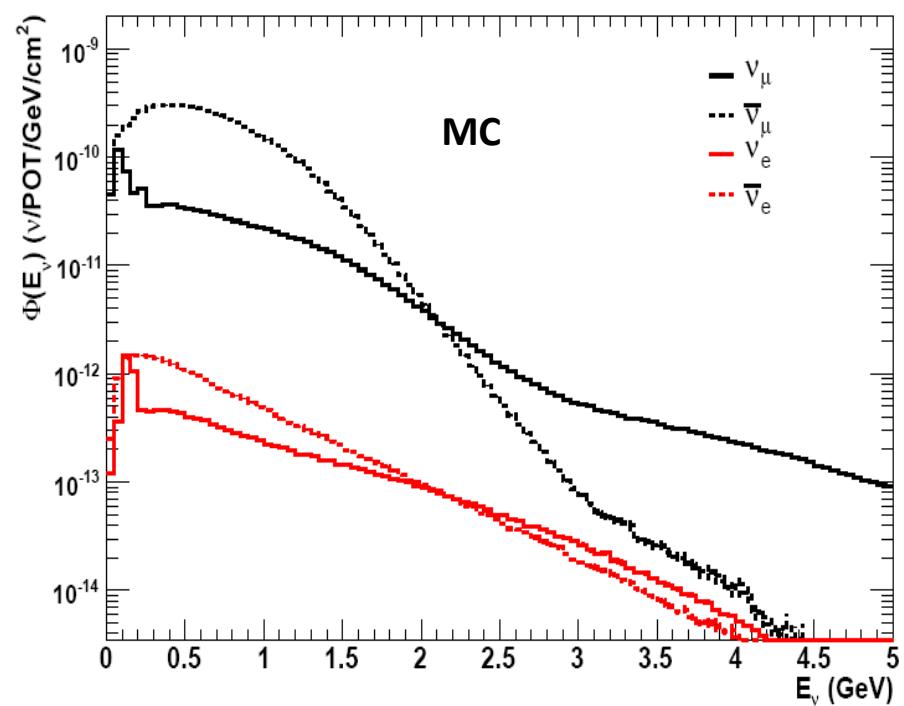
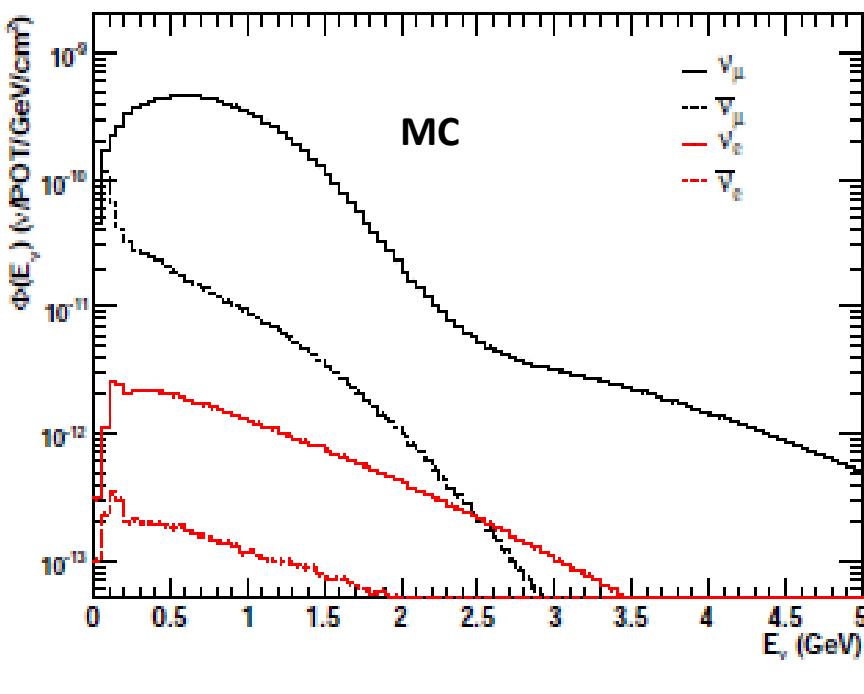
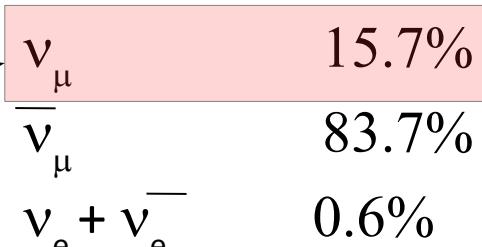
# Predicted flux

Neutrino mode



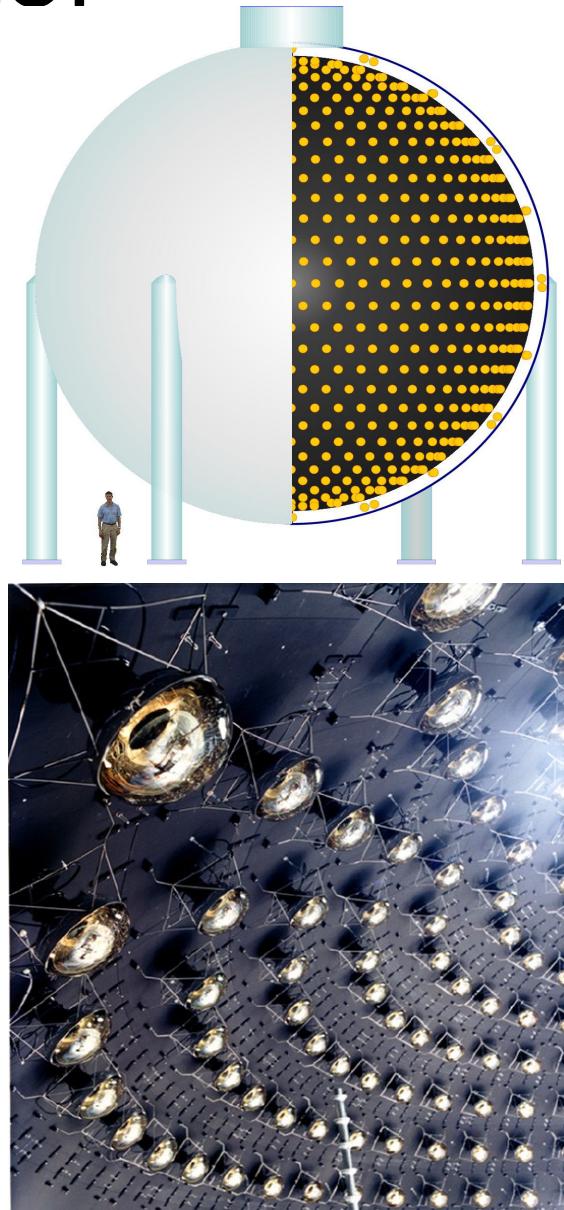
Wrong signs

Anti-neutrino mode



# MiniBooNE Detector

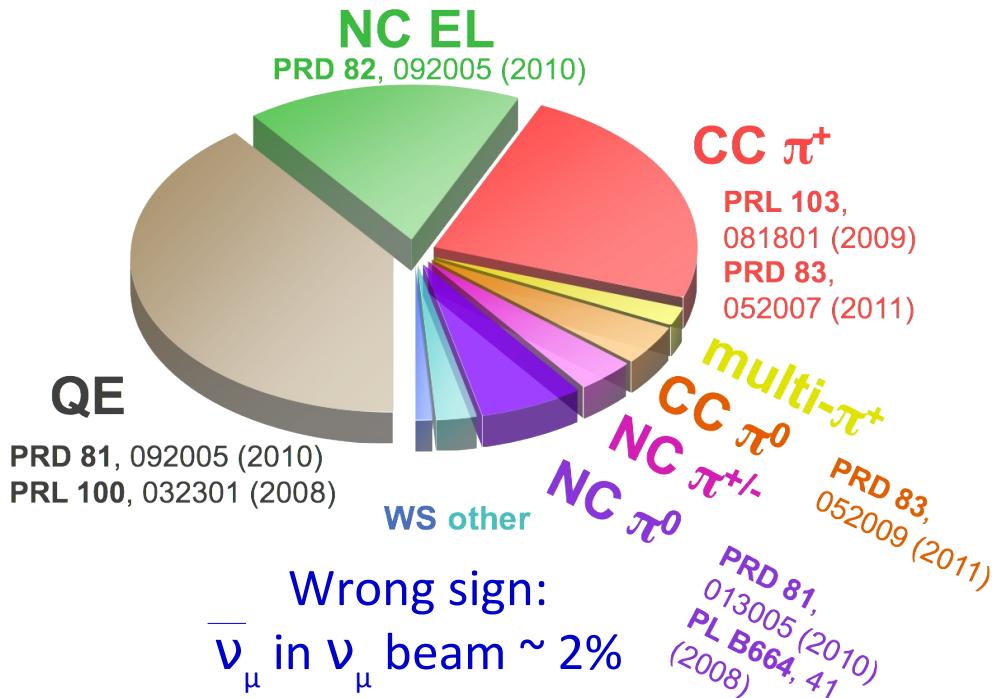
- 6.1m radius sphere filled with 800t of pure mineral oil – interactions on CH<sub>2</sub>
- 1280 PMTs inner region and 240 PMTs in outer veto region
- 10% photo cathode coverage
- 4pi detector – covers entire angular space
- Event reconstruction primarily based on Cherenkov light – best at reconstructing leptons
- Timing and topology
- Scintillation light enables measurement of NC elastic events



# Neutrino mode cross sections

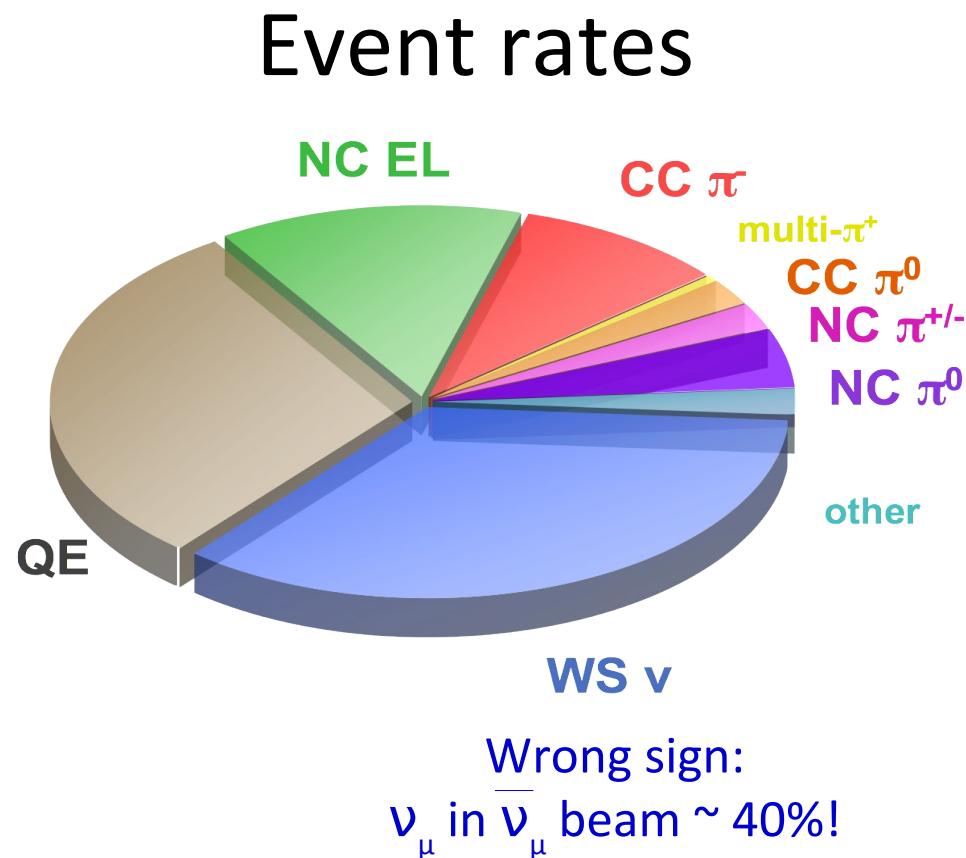
- Collected data corresponding to  $6.5 \times 10^{20}$  POT
- $\sim 1000000$  interactions in fiducial volume
- MiniBooNE has published  $\sim 90\%$  of the total neutrino mode rate

## Event rates



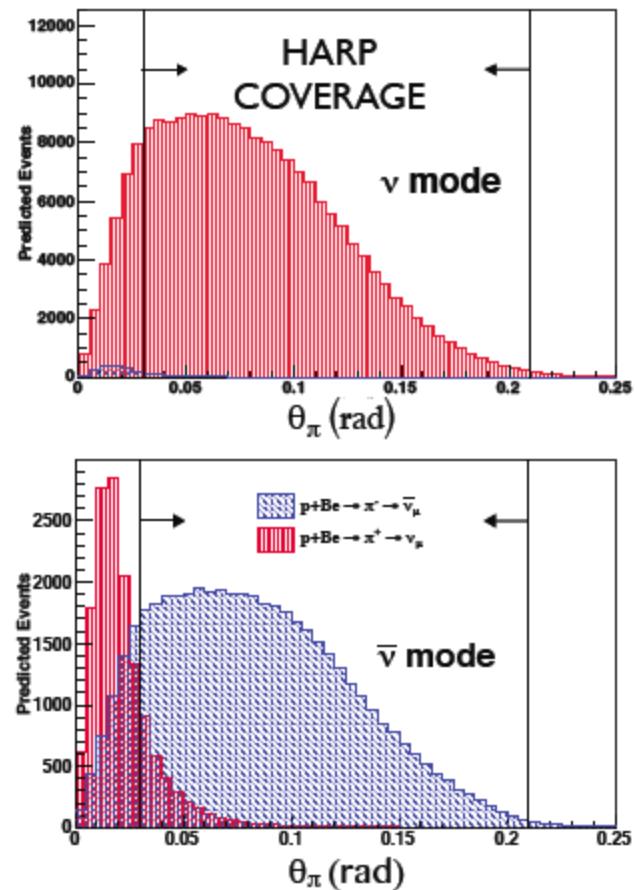
# Anti neutrino mode cross sections

- Collected data corresponding to more than  $10^{21}$  POT
- Unprecedented  $\bar{\nu}$  statistics
- Large background from wrong-sign  $\nu_\mu$ 
  - has been addressed



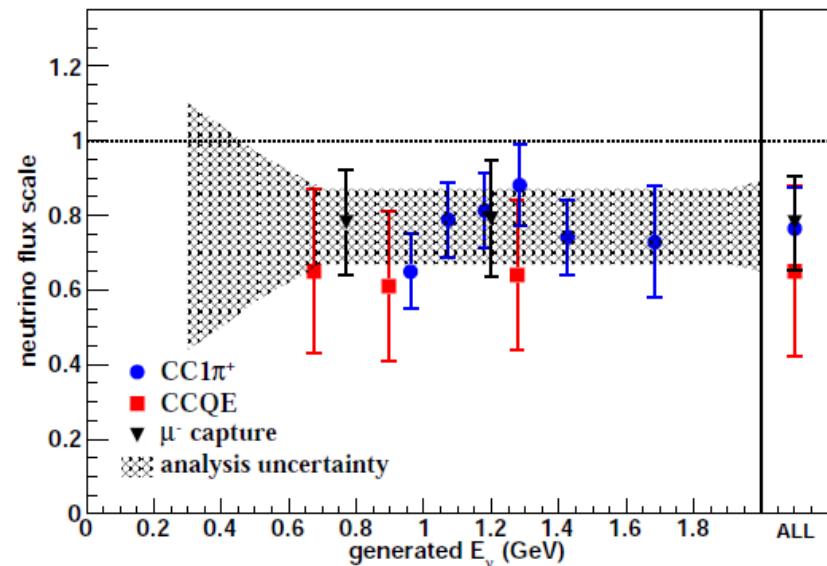
# Wrong sign background

- Pion parents contributing to wrong sign flux in antineutrino mode not covered by HARP measurement
- Have to measure this background
- No magnetic field to distinguish  $\mu^+$  vs  $\mu^-$



# WS background (cont'd)

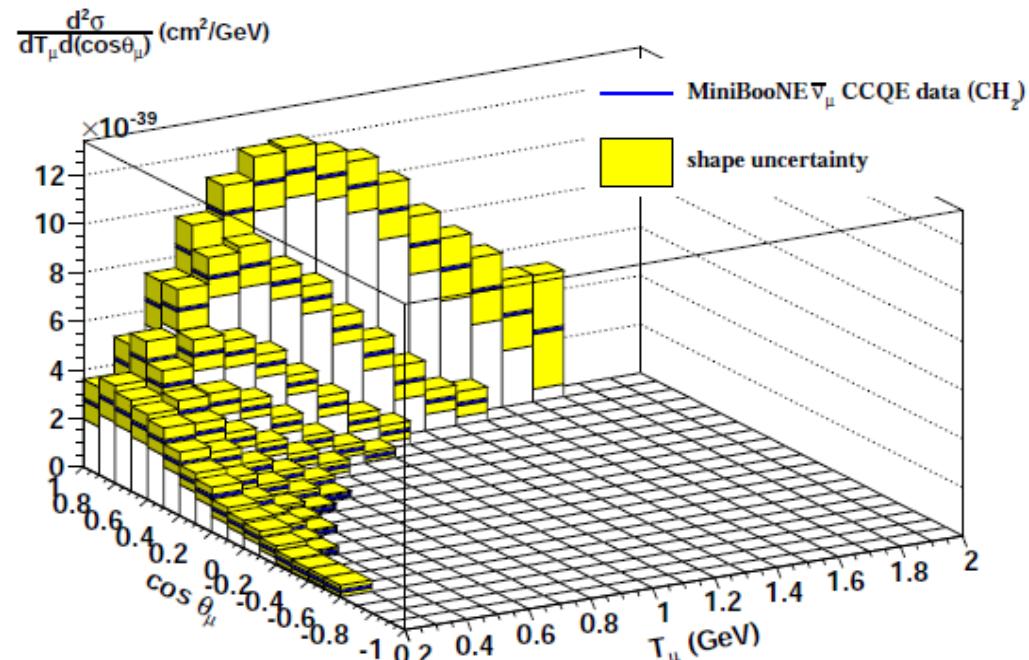
- Three methods yield consistent results
  - CC1pi<sup>+</sup> - direct rate measurement of wrong signs
  - $\mu^-$  capture – due to nuclear capture  $\nu_\mu$  CC events less likely to produce decay electrons compared to  $\bar{\nu}_\mu$
  - CCQE – angular distribution (not actually used since it depends on  $\bar{\nu}_\mu$  cross section)
- Predicted  $\nu_\mu$  flux in antineutrino mode constrained to better than 15%  
- not a dominant uncertainty anymore



# CCQE results

- 71k  $\bar{\nu}_\mu$  CCQE candidates (30% efficiency/60% purity)
- Largest background from wrong signs (measured)
- Main result is the double differential on  $\text{CH}_2$  - least model-dependent measurement possible with MiniBooNE data
- Many other cross sections available in the paper (hydrogen subtracted CCQE, Total  $\sigma(E_\nu)$ , ...)

Uncertainty type	Normalization uncertainty (%)
$\bar{\nu}_\mu$ flux	9.6
Detector	3.9
Unfolding	0.5
Statistics	0.8
$\nu_\mu$ background	3.9
CC1 $\pi^-$ background	4.0
All backgrounds	6.4
Total	13.0



# Bit of history

- In the early days saw discrepancy between neutrino data & prediction (Relativistic Fermi Gas (RFG) + $M_A = 1.0\text{GeV}$ )
- No model at the time, so tuned  $M_A$  for oscillation analysis
- Good fit with  $M_A = 1.35\text{GeV}$ , however suspected this is just effective parameter covering for nuclear effects
  - Published double differential  $\sigma(T_\mu, \theta_\mu)$
  - independent of interaction assumptions (unlike total cross section  $\sigma(E_\nu)$ )

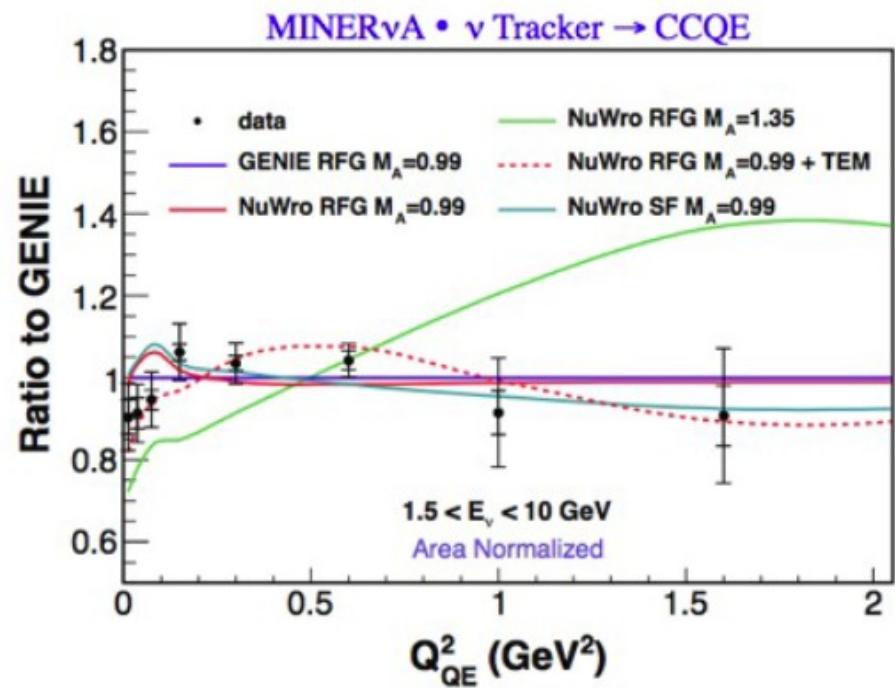
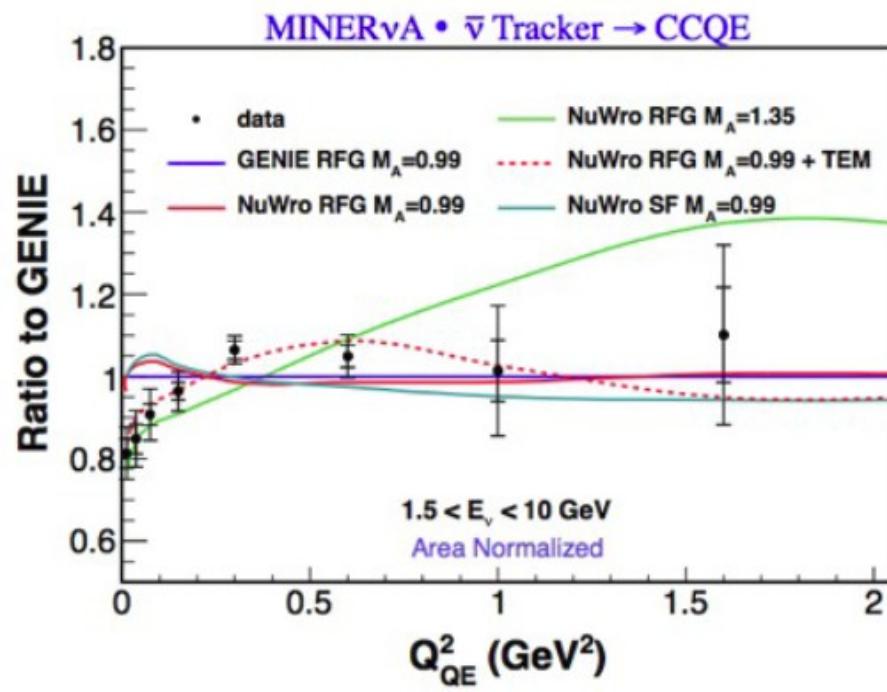
# Why $M_A$ worked well for MiniBooNE?

- Recent Minerva results prefer strongly  
 $M_A = 1\text{GeV} + \text{Transverse Enhancement Model (TEM)}$  over  
 $\text{RFG} + M_A = 1.35\text{GeV}$

*Phys. Rev. Lett. 111, 022501 (2013)*

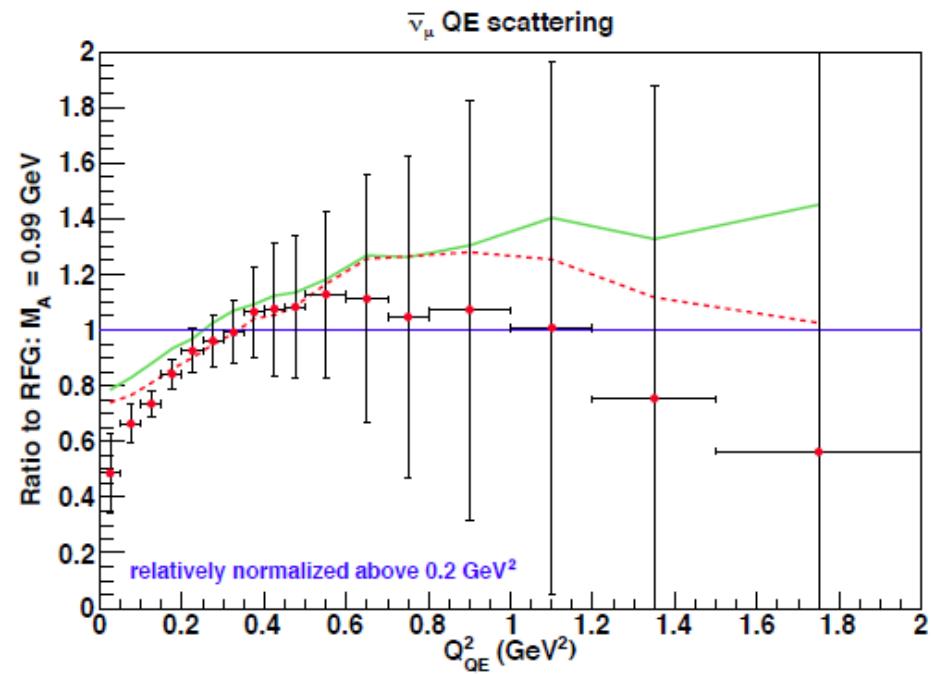
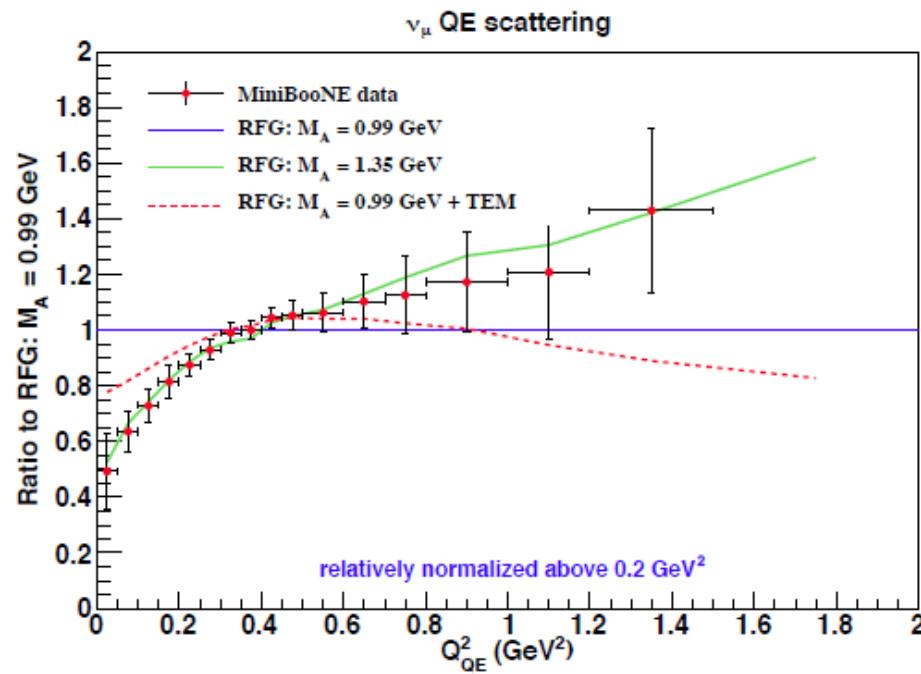
See talks by:  
Chris Marshal (Tuesday WG2 10:30)  
David Schmitz (Friday Plenary 10 8:30)

*Phys. Rev. Lett. 111, 022502 (2013)*



# Why $M_A$ worked well for MiniBooNE?

- Recent Minerva results prefer strongly  $M_A = 1\text{GeV} + \text{Transverse Enhancement Model (TEM)}$  over  $\text{RFG} + M_A = 1.35\text{GeV}$
- At BNB energies two models degenerate (above  $Q^2 > 0.2\text{GeV}^2$ )



## Forthcoming cross sections

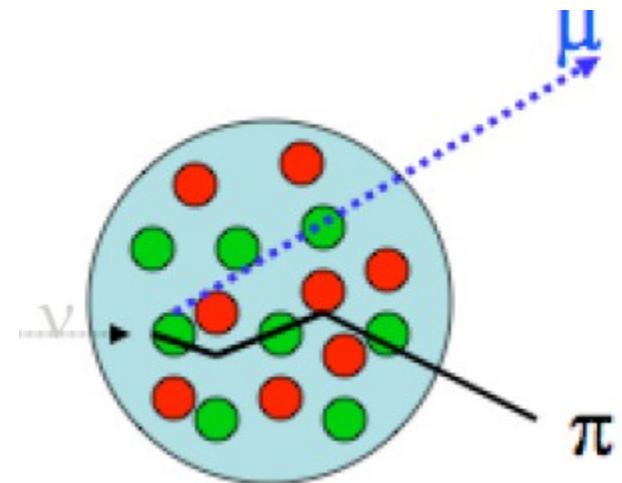
- CC inclusive
- NC elastic

# CC inclusive

- Very important to measure inclusive cross section as well as exclusive channels to build models
- Can't just add CCQE, CCpi+ and CCpi0, complicated correlated systematics
  - Each channel is a background for the others through FSI model

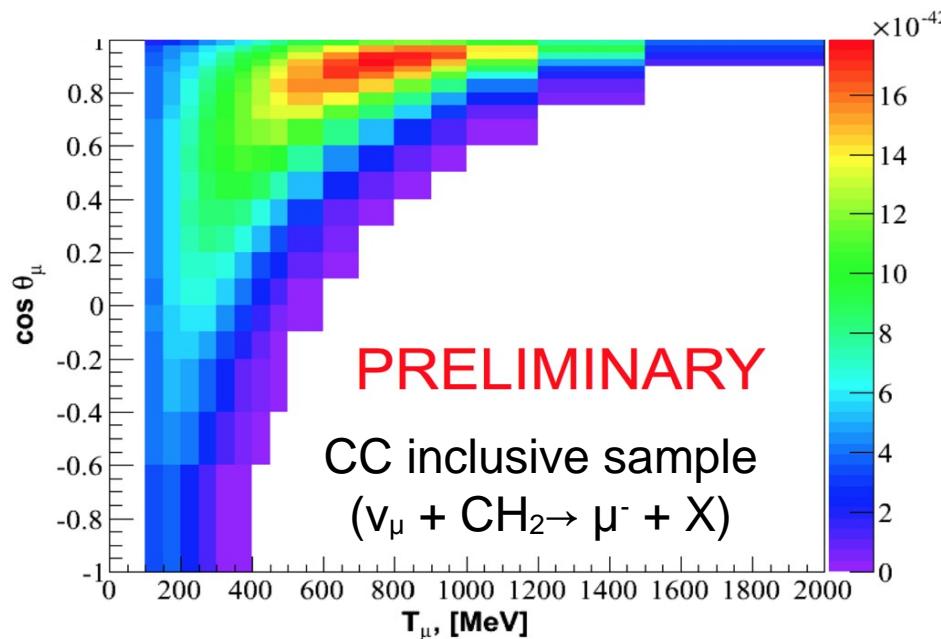
# New reconstruction

- Developed for CC inclusive measurement
- Muon kinematics from 2-track likelihood fit; second fitted track absorbs the bias due to second most prominent ring
- Significant improvement of muon kinetic energy
  - resolution is about 5% (angle resolution as before better than 1deg)



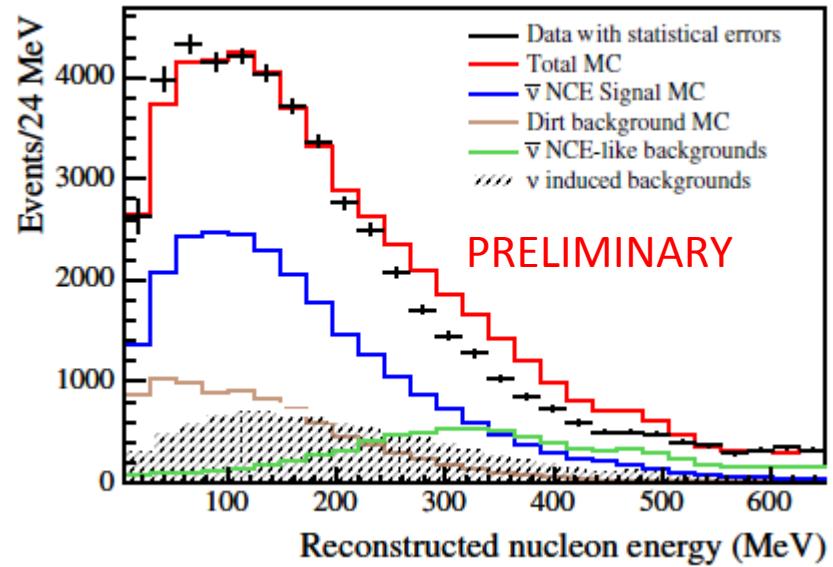
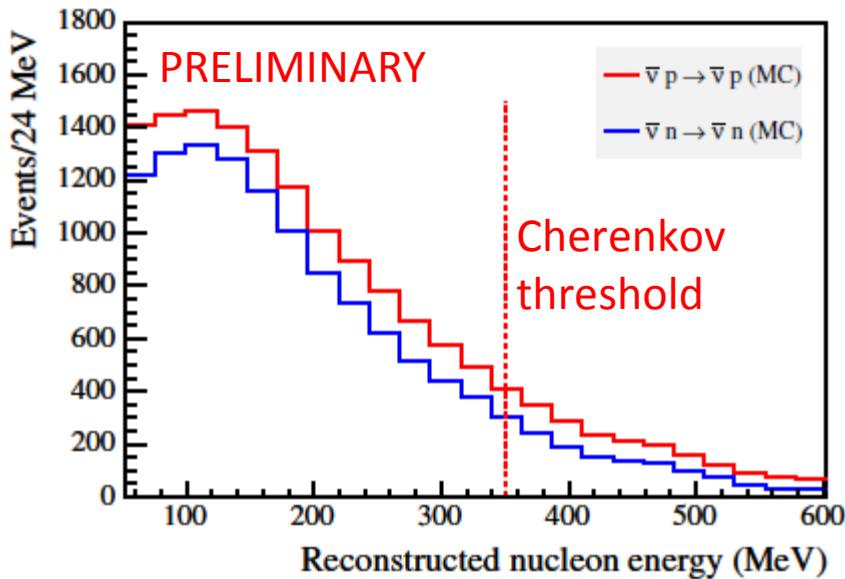
# CC inclusive results

- Selected 344k events with 96% purity
- Coming soon  $d\sigma/dT_\mu d(\cos\theta_\mu)$ , and a whole suite of other cross sections
- Full lepton reconstruction without any assumptions about nuclear target, no dependence on FSI



# NC elastic

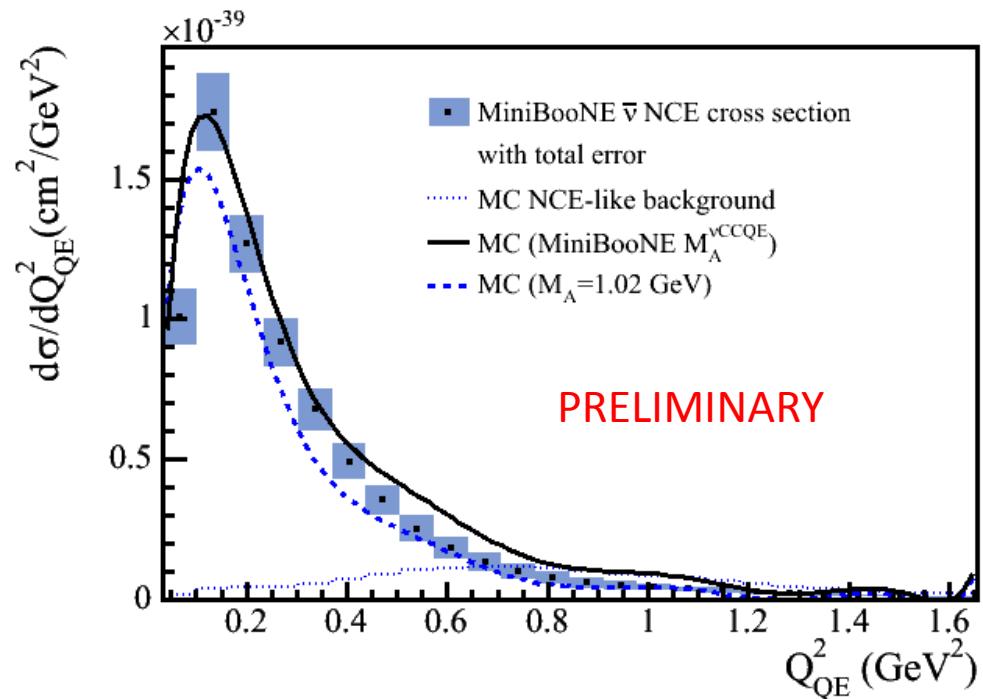
- Use scintillation light from mineral oil
- Measure n & p NC elastic interactions – some separation above Cherenkov threshold (350 MeV)
- 61k event candidates (32% efficiency, 40% purity)



# NC results

- Main result is  $d\sigma/dQ^2$
- Normalization agrees well with MC prediction (tuned to  $\nu_\mu$  CCQE data)
- $Q^2$  calculated using nucleon energy assuming interaction with an independent, at-rest target – complementary to CCQE

Error source	Normalization uncertainty (%)
anti- $\nu$ flux	6
Backgrounds	6
Detector	15
Unfolding	7
<b>Total (includes correlations)</b>	<b>21</b>



# Conclusion

- 10 years of MiniBooNE running (2002-2012)
- Extremely stable:
  - Neutrino rate/POT at 2% level
  - Energy scale stable within 1%
  - $6.5 \times 10^{20}$  POT in neutrino and  $11.3 \times 10^{20}$  POT in antineutrino mode
- MiniBooNE measured cross sections for 90% of events in neutrino mode and 83% in antineutrino mode (when new antineutrino CCQE cross sections & NC elastic are included)
- Coming soon CC inclusive and antineutrino NC elastic cross sections
- Important measurements to fully understand the cross sections and nuclear models

# Backup

# 10 years of running

- Detector and beam extremely stable
- Neutrino/POT within 2%
- Detector calibration stable at 1% level
- $6.5 \times 10^{20}$  POT in neutrino and  $11.3 \times 10^{20}$  POT in antineutrino mode

